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AN APPROACH FOR RATIONAL DESIGN AND STRUCTURAL ANALYSIS OF A HEXA-COPTER

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ABSTRACT

In the present study, an unmanned aerial vehicle is designed and analyzed. As per the requirement of lifting a payload of 1.5kg, hexacopter suits the mission profile. Rational design plays an important role in the design process which starts with the weight estimation and the chosen mission profile. A refined method is adopted based on the calculated parameters to achieve the geometry of the hexacopter. Hexacopter is designed using the design software CATIA V5. In addition to that, static stress analysis is executed using Finite element software package MSC Nastran Patran.

KEYWORDS: Hexacopter, Thrust, Lift, Propeller, Clamp, FEM Analysis, Loads and Boundary Conditions & Displacement

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Original Article

INTRODUCTION

Recent studies have shown that in the Aerospace engineering industries and academia, the interest in electrically powered, unmanned aerial vehicles has skyrocketed during the past few years. This is mostly due to the role they are playing within a wide range of military and civilian applications. UAVs come in all sizes, fixed wing or rotary, and are used to perform various applications [12], largely in the field of remote sensing [13]. Factors like simple configuration, real time and remote sensing, simplicity of use (even in confined spaces) and other advantages like hovering and vertical take-off and landing capabilities, which all makes them interesting. Multi rotor systems exhibit increased maneuverability and a faster response to external disturbances together with a more compact size. Hex copter is a multi-rotor helicopter rotor craft, that is lifted and propelled by six rotors. Hex copter use three sets of identical fixed pitched propellers; three clockwise (CW) and three counter-clockwise (CCW). These uses variation of RPM to control the lift and torque. Control of vehicle motion is achieved by altering the rotation rate of one or more rotor disks, thereby changing its torque load and thrust/lift characteristics. This craft has more maneuverability and flying power than a quad copter.

NEWTON'S SECOND LAW

Newton's second law of motion can be formally stated as follows: The acceleration of an object as

produced by a net force is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the object.

$$F = ma \tag{1}$$

For constant velocity, acceleration is zero (a=0). Thus the sum of the forces is equal to zero. A long horizontal plane:

$$F_{Thrust} - F_{Drag} = \tag{2}$$

Since this is for a constant velocity, the aircraft is either moving or at rest. An analysis in the vertical direction will produce similar results.

$$F_{Lift} - F_{Weight} = \tag{3}$$

For steady level flight the thrust must equal the drag and the lift must equal the weight.

In order to gain altitude, the force of lift must be greater than the force due to gravity.

Similarly, in order to accelerate the vehicle, the force of thrust must be greater than the force of drag. For the multi-rotor to perform different types of movements, the sum of the forces and torques have to follow a certain pattern.

MOMENTUM THEORY

For an actuator disk of area A, with uniform induced velocity $\boldsymbol{v}$ at the rotor disk, and with ρ as the density of air, the mass flow rate through the disk area is:

(4)

By conservation of mass, the mass flow rate is constant across the slipstream both upstream and downstream of the disk (regardless of velocity). Since the flow far upstream of a helicopter in a level hover is at rest, the starting velocity, momentum, and energy are zero[10][11].

If the homogeneous slipstream far downstream of the disk has velocity ɯ, by conservation of momentum the total thrust T developed over the disk is equal to the rate of change of momentum, which assuming zero starting velocity is:

(5)

DESIGN

RATIONAL DESIGN IN MACHINE DESIGN

This type of design depends upon mathematical formulae of the principle of mechanics [14].

DESIGN SOFTWARE

CATIA V5 is designing software mainly used in aerospace and automobile industries for designing components.

DESIGN DEVELOPMENT

The first step for design was the determination of the type of UAV to be built. This is based on the purpose of the UAV and therefore the structural size and weight required [1] [8]. From the various applications of UAVs we choose to build one for multispectral thermal imaging. To begin with the design of a UAV for this purpose, the weight requirements

were calculated as:

Table 1: Weight Requirements

Model Weight	Payload Weight
1.5 kg (~ 15 N)	1.5kg (~ 15 N)

THRUST REQUIREMENTS

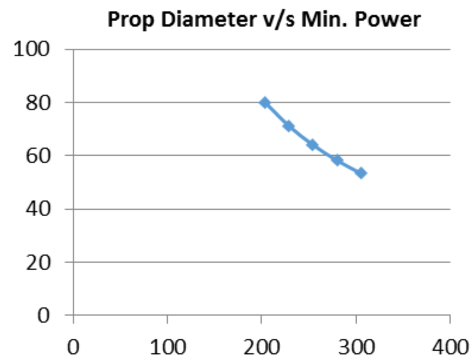
Design factor- 1.5, T/W ratio- 33

Table 2: Thrust Requirements

Parameters	Values	Units
Estimated Weight	3	Kg
Design Weight	4.5	Kg
Thrust Required	13.5	Kg

SELECTION OF PROPELLER SIZE

A study was carried out on the different propeller sizes available in the market and disk loading, minimum and maximum power, hover velocity and maximum velocity were compared for each propeller size [2] [10].

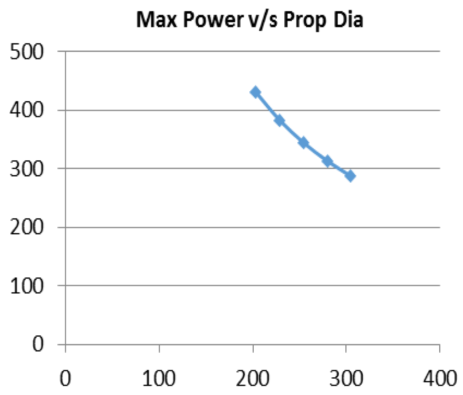


Graph 1: Propeller Diameter Variation with Min Power Required

Table 3: Propeller Diameter Variation with Min Power Required

Diameter (mm)	Min. Power (watt)
203.3	80.04426655
228.6	71.18547414
254	64.06692673
279.4	58.24266066
304.8	53.38910561

Power developed by the propeller, in hover condition, decreases as the size of the propeller increases. But with small propellers, the disk loading on the propellers is high. Hence, we choose a propeller based on the power required from each propeller-motor combination. A power of 53 watts is found optimum for the hex copter we are designing.

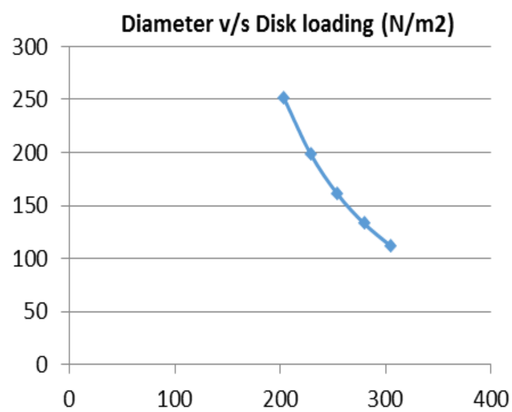


Graph 2: Propeller Diameter Variation with Max Power Required

Table 4: Propeller Diameter Variation with Max Power Required

Diameter (mm)	Power (watt)
203.3	430.6838577
228.6	383.0184964
254	344.7166468
279.4	313.3787698
304.8	287.2638723

Disk loading is defined as the ratio of thrust produced by the propeller and the rotor disk area. For optimum power with less disk loading on the propellers, the propeller size of 304.8 mm is selected.



Graph 3: Propeller Diameter Variation with Disk Loading

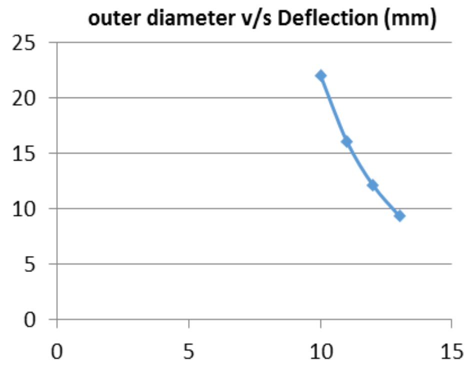
Table 5: Propeller Diameter Loading Variation with Disk Loading

Diameter (mm)	Disk loading (N/m^2)
203.3	251.9668156
228.6	199.2808892
254	161.4175203
279.4	133.4029093
304.8	112.0955002

SELECTION OF ARM DIMENSIONS

The selection of arm dimensions is based on the bending stress and deflection calculations. Circular cross-section was selected since the loads acting on the Hex copter arms are a combination of bending and torsion loads. Hollow cross-section with a thickness of 2mm was fixed to reduce the weight and ensure adequate torsion strength to ensure it would not be over-stressed.

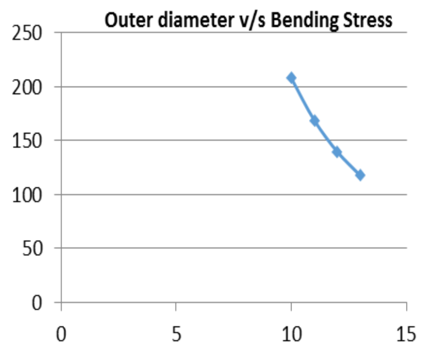
Arm deflection with different arm diameters of constant thickness of 2mm is compared. It is found that deflection decreases within the arm diameter. But, we selected an arm with outer diameter whose deflection is within the 8-10% limit of the arm length.



Graph 4: Deflection with Outer Diameter

Table 6: Deflection with Outer Diameter

D_o	Bending Stress (N/mm^2)
10	22.05142566
11	16.1128239
12	12.12664094
13	9.352846056



Graph 5: Stress with Different Cross sectional Diameter

Table 7: Stress with Different Cross sectional Diameter

D_o	Bending Stress (N/mm^2)
10	208.1637409
11	169.0042253

12	139.913334
13	117.7201845

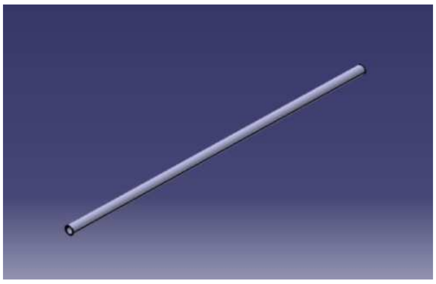


Figure 1: Arm for Hex Copter

Though we obtain lesser bending stress with larger arm diameters, weight consideration limits this increase. Also, an arm diameter with bending stress well within the yield limit of the material being used is chosen.

CLAMP DESIGN

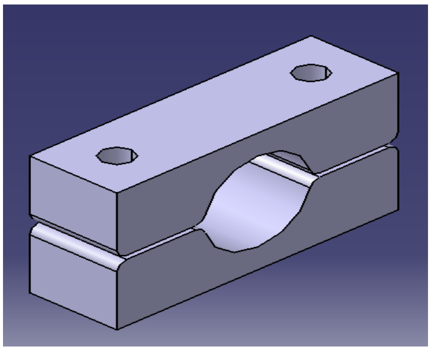


Figure 2: Clamp for Hex Copter

Clamp design is such that it can transfer the stresses acting on the arms to the plate structure. It is designed with a fit tolerance with respect to the arm diameter and the holes for bolting of clamps are calculated keeping the min. edge distance. The number of clamps and its spacing is decided to reduce the vibration of arms.

HEX COPTER PLATE DESIGN

The Hex copter plate is designed to accommodate all the equipment necessary from the battery to the sensors and also make space for mounting the camera. Hexagonal shape of the plate was found to have the advantage of lesser plate area and hence lesser weight as opposed to a circular plate.

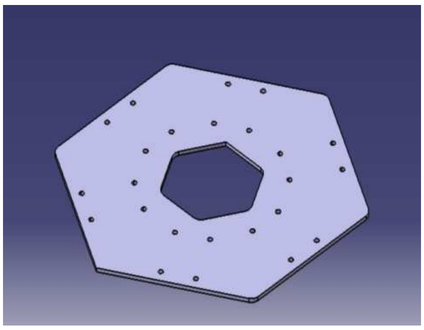


Figure 3: Plate for Hex Copter

HEX COPTER ASSEMBLY

All the parts designed as shown above are assembled in CATIA V5 to obtain the whole assembled model. The assembly is shown below. Our rational design of Hex copter is completed as per the Design considerations mentioned above with respective analytical design calculation (Estimated).

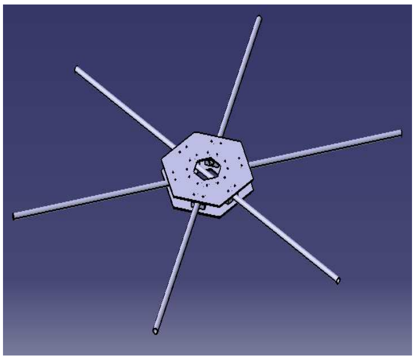


Figure 4: Assembly of Hex Copter

The assembled hex copter is to be analyzed by analysis software Like ANSYS, MSC. Nastran, MSC. Patran etc. Once the analysis is carried out, then validation process is carried to further optimize the design.

MATERIAL SELECTION

For further design, we had to choose the material with which the Hexacopter is to be built. Aluminium and composites are the two most commonly used materials in the aerospace industry for the frame structure.

Composites have great electrical, thermal and physical proprieties with lightweight but under loads, carbon fibers bend, but they do not remain permanently deformed. Instead, once the ultimate strength of the material is exceeded, it will fail suddenly. Also, composites are expensive and not readily available. Hence, we choose aluminium since it is readily available and has excellent physical properties with light weight required for a Hexacopter[8].

Aluminium Alloy 2024 is an aluminium alloy, with copper as the primary alloying element. It is used in applications requiring high strength, weight ratio, as well as good fatigue resistance. It is weldable only through friction welding, and has average machinability.

Table 8: Mechanical Properties

Parameter	Value
Density	2.77 ×1000 kg/m3
Elastic Modulus	70-80 GPa
Tensile Strength	185 MPa
Yield Strength	76 MPa
Hardness	47 HB500*

*HB – Brinell hardness number of 500 kgf

Composition: Al 2024 composition roughly includes: Copper 4.3-4.5%; Manganese 0.5-0.6%; Magnesium 1.3-1.5%; Zinc, Nickel, Chromium, Lead, Bismuth <0.5%

FINITE ELEMENT ANALYSIS

A. Software: MSC NASTRAN and PATRAN

B. Analysis

MSC.Patran can access geometry from an external CAD system user file. The Hexacopter model from Catia is imported into Patran in the form of respective data base file.

C. Element Properties and Material Properties

Element properties are the properties of the elements created by parameterization. These properties are different for each type of geometry.

D. Meshing

Before generating the finite element mesh in the hexacopter, it is necessary to create a separate group. This is to keep the Geometry model separate from a Finite Element Model. This makes it easier to select and display the Geometry model separately from the Finite Element Model. Groups are like "named components". Each group has its own name and contains entities. The individual components which are grouped are individually Meshed; we use Hexa Mesh for meshing the hexacopter, since the whole geometry is covered which leads to accurate results. Checks for equivalence, connectivity, element quality, duplicate element and others are done.

E. Loads and Boundary Conditions

As we know, the load condition and boundary conditions of the hexacopter which is obtained from analytical method, similar load condition and boundary conditions are created in the Software on the hex copter.

- Initially, since we know that the clamps are fixed to the plates with fasteners, 3D mesh has been applied to clamp and 1D beam element has been applied to arrest the clamp.
- Then a MPC (Multi Point Constraint) is created with a RBE3 and RBE2 Model at the CG (Centre of Gravity) and at clamp-plate fastener holes respectively.
- Since the Thrust force is acting at the tip of the arms due to the power plants, a MPC is created at every tip of the arm and the Positive Fz Load due to thrust is applied.
- The midpoint (node) of the 1D beam element has been assigned 6DOF. (TX, TY, TZ)

After executing these steps the model is solved, it is time to investigate the results of the analysis. With a thorough check for problems that may have occurred during solution. Next, reaction loads at restrained nodes should be summed and examined. Reaction loads that do not closely balance the applied load resultant for a linear static analysis should cast doubt on the validity of other results.

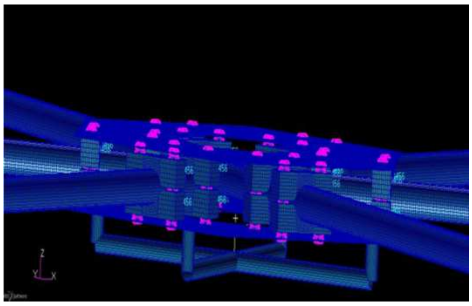


Figure 5: Completely Discretized Meshed Model

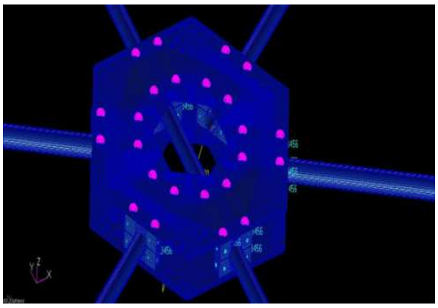


Figure 6: Iso View

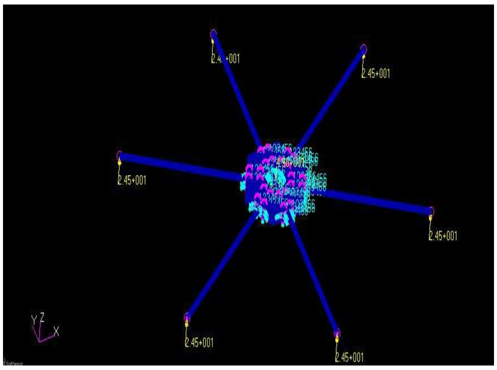


Figure 7: Load Application at the end of the Lifting Arms

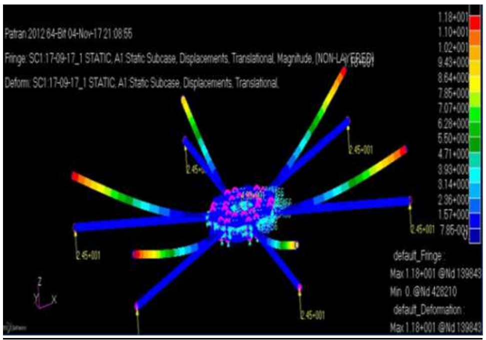


Figure 8: Overall Body Displacement

Displacement of the body

Max. Displacement = 11.8 mm

Min. Displacement = 0 mm

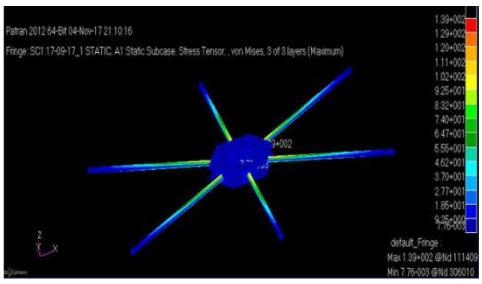


Figure 9: Overall Body Von Mises Stress

Von Mises Stress on the Body

Max. Stress = 1.39×10^{2} N/mm^2

Min. stress = 7.76×10^{-3} N/mm^2

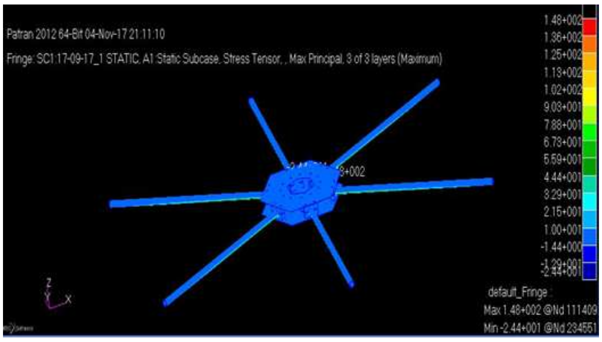


Figure 10: Maximum Principle Stress of Overall Body

Maximum Principle Stress on the Body

Max. Stress = 1.48×10^{2} N/mm^2

Min. stress = -2.44×10^{1} N/mm^2

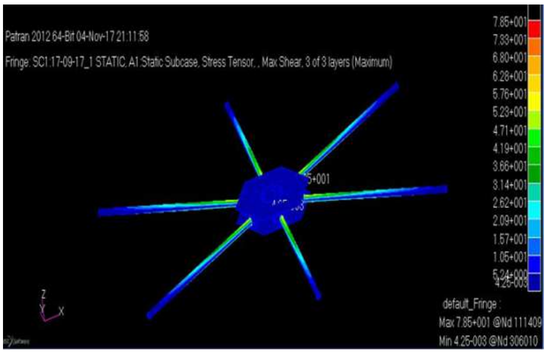


Figure 11: Maximum Shear Stress of Overall Body

Maximum Shear stress on the Body

Max. Stress = 7.85×10^{1} N/mm^2

Min. stress = 4.25×10^{-3} N/mm^2

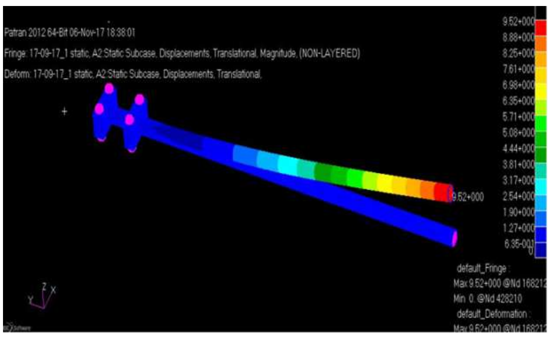


Figure 12: Displacement of the Arm

Displacement of the Arm

Max. Displacement = 9.52 mm

Maximum displacement of 9.52mm is observed at the end of the lifting arm, which depicts that the loads acting at the end of the arm is due to the motors running at high rpm which causes a displacement in them over time or cycles.

F. Validations

The results obtained from the analysis can be validated for using different methods. **Reserve Factor Validation** is the most popular method. Reserve factor is defined as the ratio of ultimate stress to actual stress. [10]

A reserve factor of greater than 1 means the system is safe. Reserve factor of 2 or more is very safe. A RF of less than 1 means the system fails.

Table 9: Von Mises Stress

VON MISES STRESS		
Part	**Induced Stress**	**RF**
Overall body	139	3.45
Arm	132	3.63
Clamp	87.8	5.46
Mounting plate	13.9	34.53

Von Mises Stress is mainly used whenever ductile material is selected for designing a structure. This generally means that on application of loads ductile material undergoes shear failure and not the sudden 90^0 brittle material failure. It is considered to be a safe haven for design engineers, using which one can that the material or component will fail, if the maximum von mises stress induced in the material is more than the strength of the material.

Table 10: Max Principle Stress

MAX PRINCIPLE STRESS		
Part	**Induced Stress**	**RF**
Overall body	148	3.24
Arm	142	3.38
Clamp	121	3.96
Mounting plate	148	3.24

Table 11: Max Principle Shear

MAX PRINCIPLE SHEAR		
Part	**Induced Stress**	**RF**
Overall body	78.5	3.69
Arm	74.7	3.88
Clamp	50.3	5.78
Mounting plate	78.5	3.69

CONCLUSIONS

The results obtained from analysis depict that the values of the stress and shear are well within the structural limits of the material applied. This shows that the body can handle higher stresses and shear forces.

The validation results depict that the RF values are higher than 1.5, which means that further weight optimization

can be done by reducing the dimensions of the clamp, arm and mounting plate. The values even depict that our hexacopter design is capable of lifting heavier payload than that was initially assumed.

REFERENCES

1. *A.V. Javir, P. Ketan, D. Santosh, and P. Nitin, "Design Analysis and Fabrication of Quadcopter", Journal of the International Association of Advanced Technology and Science, vol. 16, March 2015.*
2. *B.H. Stearns, E. H. Charles, and G. Ashok, "Development and Testing of a Passive Variable Pitch Propeller", Journal of Aircraft, vol. 52, pp.748-763, 2015.*
3. *K. Van, J. N. Sorensen, and V. L. Okulov, "Rotor Theories by Professor Joukowsky: Momentum Theories", Aerospace Sciences-Elsevier Journal, pp. 1-18, 2015.*
4. *T.S. Alderete, "Simulator Aero Model Implementation", NASA AMES RESEARCH CENTER, CALIFORNIA.http://www.aviationsystemsdivision.arc.nasa.gov/publications/hitl/rtsim/Toms.pdf.*
5. *M. Cefalo, J.M. Mirats-Tur (2011) "A Comprehensive Dynamic Model For Class-1 Tense Gritty Systems Based On Quaternions", International Journal of Solids and Structures.*
6. *R. F. Stengel (2004) "Flight Dynamics", (Princeton University Press).*
7. *S. Bhandari1, S. Pathak1, R. Poudel1, R. K. Maskey2, P. L. Shrestha1 and BinayaBaidar, "Design and Development of Hexa-copter for Environmental Research", Department of Civil and Geomatics Engineering School of Engineering, Kathmandu University, Dhulikhel.*
8. Sharma D.K & Kumar A*, Identification and Quantification of Podophyllotoxin from Podophyllum Hexandrum by ESI-LC/MS/MS, International International Journal of Applied, Physical and Bio-Chemistry Research (IJAPBCR), Volume 5, Issue 3, November - December 2015, pp. 1-8*
9. *R.W. Prouty, "Helicopter Performance, Stability and Control", 2003, Krieger publishing Company, p. 1-10.*
10. *"Principles of Helicopter Aerodynamics" by J GordanLieshman, Cambridge university press.*
11. *The Design and Construction of a High Endurance Hexacopter suited for Narrow Corridors* by J. Verbeke, D. Hulens, H. Ramon, T. Goedemé and J. De Schutter.*
12. *Chandra Kumar Dixit & A. K Srivastava, Hybrid The Structural Properties & Ferroelectric Properties of Succinic Acid Di-Sodium SalHexa Hydrate, International Journal of Metallurgical & Materials Science and Engineering (IJMMSE), Volume 3, Issue 1, January - March 2013, pp. 1-8*
13. *R. Austin, "Unmanned Aircraft Systems: UAVS Design, Development and Deployment", 2010, Wiley, p. 253-279.*
14. *Luccio, "Remote Sensing by Remote Control: UAVs become invaluable assets", Geospatial Exploration Products BAE Systems, 2009, http://www.geospatialexploitationproducts.com*
15. *UNMANNED AIRCRAFT SYSTEMS UAVS DESIGN, DEVELOPMENT AND DEPLOYMENT by Reg Austin Aeronautical Consultant.*